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FLUID HYDRAULICS

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SOME CONSIDERATIONS ON TWO-PHASE  
FLUID HYDRAULICSMario Silvestri  
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Two-phase fluids present more than a dozen types of outflow, in contrast to monophasic fluids for which there are only two: laminar and turbulent. The C.I.S.E. laboratories have been particularly interested in dispersed annular outflow, which can be defined as outflow characterized by high linear velocity and by a liquid phase distribution in the form of droplets in the gaseous phase and a very thin layer adhering to the walls of the outflow channel.

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Some interesting conclusions have been deduced to date from an examination of the experimental results concerning the thickness of the liquid film as a function of different physical variables coming into play (dynamic variables and physical properties of the two phases in motion), and concerning the distribution of the liquid phase in the center of the canal. Experiments with heat flux have confirmed the hypothesis that the liquid film on the heated walls plays a very important role in determining the heat exchange mechanism.

*Auth*NOMENCLATURE

D(cm)	Pipe diameter
f	Friction factor

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Note: Numbers in the margin indicate pagination in original foreign text.

$g$ (cm/s <sup>2</sup> )	Gravity acceleration
$G$ (g/cm <sup>2</sup> s)	Specific yield
$G'$ (g/cm <sup>2</sup> s)	Specific yield with respect to the available cross section (having the diameter $D-2s$ )
$h$ (W/cm <sup>2</sup> °C)	Thermal exchange coefficient
$s$ (cm)	Thickness of liquid film
$\gamma$	Yield ratio: ratio in weight between the yield of the gaseous phase and the total yield
$\Gamma$ (g/s)	Total yield
$\Delta T$ (°C)	Temperature difference
$\Delta p / \Delta z$ (dyne/cm <sup>3</sup> )	Pressure decrease per unit of length
$\lambda$ (W/cm °C)	Thermal conductivity
$\mu$ (poise)	Viscosity
$\rho$ (g/cm <sup>3</sup> )	Density
$\tau$ (dyne/cm <sup>2</sup> )	Unitary tangential tension
$\Phi$ (W/cm <sup>2</sup> )	Heat flux

## INDICES

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a	In heat flux experiments, with zero flux
c	With respect to "burn-out"
c	With respect to the evaporation process

g	With respect to the gaseous phase
l	With respect to the liquid phase
m	With respect to the mixture
o	With respect to the annular-dispersed transition

1. Two-phase outflow can be defined as an outflow where two distinct phases are present: gas-liquid, gas-solid, liquid-solid. In the article which follows, we are only concerned with gas-liquid systems in which the gas and the liquid can be two distinct substances or one single substance.

Two-phase outflows can pertain to a great many more types than is the case with monophasic outflows, in which only a laminar outflow and a turbulent outflow can be distinguished. In addition, the pipe arrangement (vertical in an upwards direction or in a downward direction, horizontal, inclined) is of great importance, considering the fact that certain types of outflow are only possible in some of these arrangements.

For purposes of abbreviation, from this point on we shall designate as "dispersed outflows" the two-phase outflows having relatively high yield ratios, characterized by the continuity of the gaseous phase, while the liquid is to a great extent dispersed in the form of droplets in the gas current. Nevertheless, in general, one part of the liquid forms a continuous film adhering to the walls of the pipe (Figure 1). Annular outflows designate outflows in which the largest part of the liquid phase is distributed in this way in contact with the walls. The outflow type, both under adiabatic conditions and with heat transmission, depends on

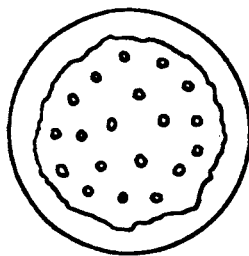


Figure 1

the specific yields, the geometric conditions, and the physical properties of the two phases.

In this latter case, as the yield ratio changes, several different types of outflow can occur at the same time along the pipe. For example, in a vertical pipe fed by liquid water, one can pass from a monophasic regime to a regime with local ebullition on the heated wall, then to an ebullition regime within the fluid mass, to dispersed annular outflow, to purely dispersed outflow, and finally to superheated vapor, i.e., to monophasic outflow again. The transition from ebullition within the fluid mass to dispersed annular outflow occurs when the section of the pipe occupied by the vapor is almost equal to that occupied by the liquid. This transition can be accompanied by yield oscillations under certain conditions, which characterizes another type of outflow called "stopper" outflow, where, periodically in time, the zones richer in water are followed by zones richer in vapor.

Dispersed outflow which is always present in the transition from the liquid phase to the gaseous phase has been studied in our laboratory both under adiabatic conditions and with heat transmission.

2. Dispersed outflow under adiabatic conditions has been studied in the case of a water-vapor system for water, and in that of systems having two components in a high pressure circuit at room temperature.

The principal characteristics of this circuit can be summarized as follows:

a) Type of gas: argon or nitrogen under varied pressure; this made it possible to study the effect of gaseous phase viscosity without changing the density;

b) Gas pressure: from  $25 \text{ kg/cm}^2$  to atmospheric pressure. With one gas, this made it possible to study the effects of a change in density without an appreciable change in viscosity;

c) Type of liquid: water and ethyl alcohol. This made it possible to study the effect of a change in surface tension without changing the viscosity and the density in a noticeable way;

d) Temperature: by changing the water temperature from  $14$  to  $37^\circ\text{C}$ , it was possible to vary the viscosity of the liquid phase by a factor of close to two without an appreciable change in its density or in its surface tension;

e) Specific yields and yield ratios:

$G_{\text{tot}}$  from  $30$  to  $300 \text{ g/cm}^2\text{s}$ ,

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X from 8% to 80%;

f) Geometry: cylindrical and annular pipes.

Among those experiments which were carried out by changing the different physical properties, we would like to point out the following:

a') Measurement of the liquid film thickness on the walls by measuring its electric resistance between two upright sections of the pipe;

b') Measurement of the distribution of the phases and the velocities within the pipe by means of a Pitot tube and by an isokinetic probe;

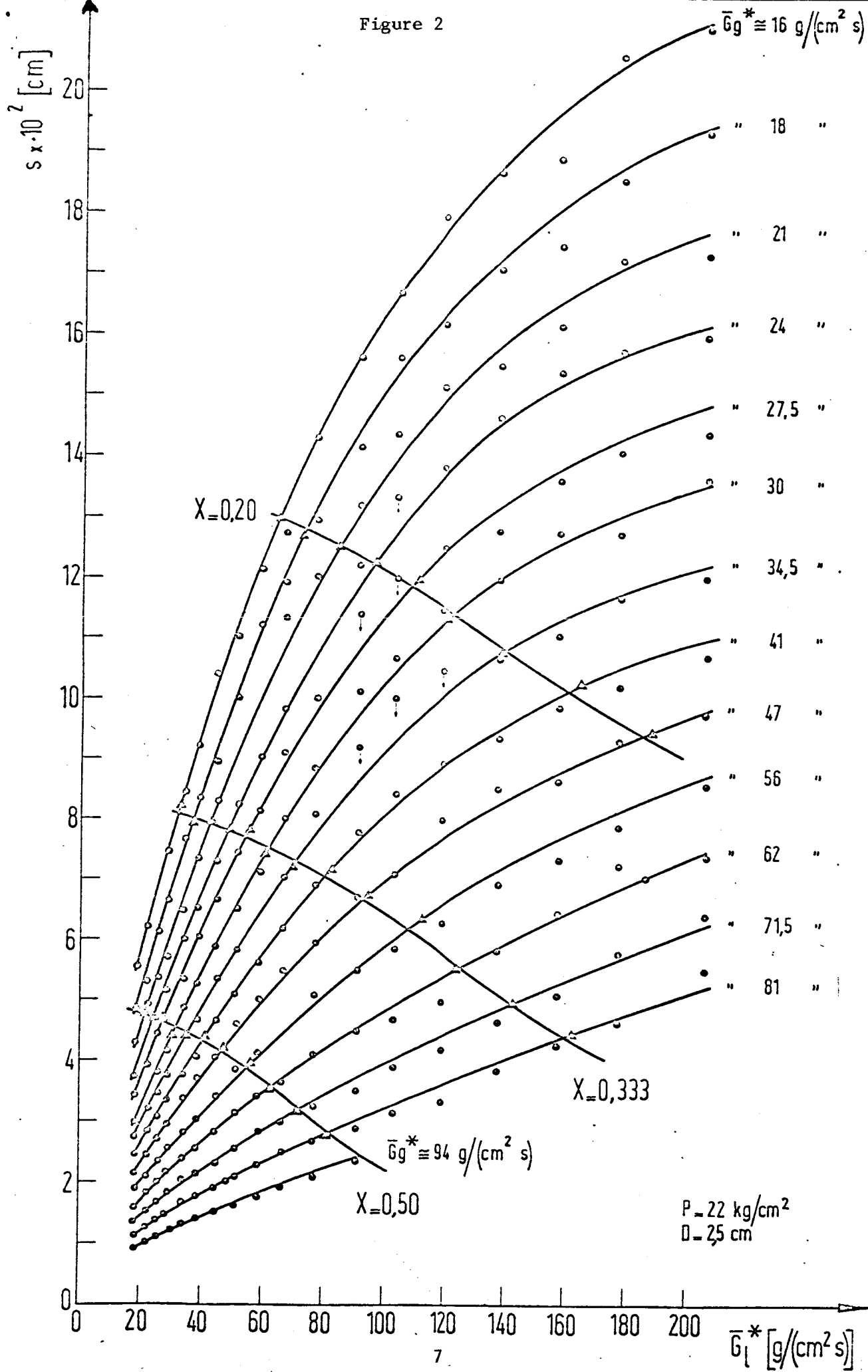
c') Measurement of the total amount of liquid in the test section by means of a beta ray absorption;

d') Measurement of the rapid fluctuation in pressure with a "pressure receiver" having low inertia;

e') Measurement of the total pressure loss along the pipe by means of a differential, column manometer.

3. Without wishing to go into the details of the measurements here, we would like to point out that the most interesting physical quantities are the velocity distribution of the two phases within the pipe and the portion of the section occupied by the liquid phase. The thickness of the liquid films on the walls plays an important role in determining this quantity. The remainder of this article is devoted to a presentation and a discussion of the results obtained in the case of cylindrical pipes. Figure 2 shows the results, obtained under the conditions specified above, derived from the measurement of the film thickness using the method

Figure 2



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described under section a' in paragraph 2. It can be seen that the lines corresponding to constant yield ratio show gaussian behavior, as a function of  $G_1$ . Since it can be assumed that the tangential tension, to which the liquid film on the wall is subjected, is proportional, in the first approximation, to the square of the total specific yield which - for a constant yield ratio - is proportional to the specific yield of the liquid, an examination of the curves suggests the following proposition:

$$ds = -ksd\tau \quad (1)$$

i.e., the thickness variation corresponding to constant yield ratio is proportional to the thickness itself and to the variation of the surface tension  $d\tau$  at the dispersed contact point liquid-center.

The integration of equation (1) must be made with several precautions. Since the outflow is dispersed, one can assume that its physical limit is purely annular outflow, without the liquid droplets being carried along in the center of the flow. The limiting condition  $s = s_0$  can then be made (thickness for purely annular outflow) for  $\tau = \tau_0$ , where  $\tau_0$  is the tangential tension for annular outflow. We then have:

$$\frac{s}{s_0} = e^{-k(\tau - \tau_0)} \quad (2)$$

Since  $\tau_0 \ll \tau$  in all the cases studied,  $s_0$  can be determined in practice by extrapolation of the experimental value of  $s$  for  $G_1 \rightarrow 0$ . However, one should not forget that this extrapolation has no physical significance, because, by reducing  $G_1$  to 0 for the constant yield ratio, outflow types would be encountered which are not represented by (1).

The value of  $s_0$  can also be calculated theoretically, provided that an hypothesis is made regarding the phenomenon which determines the transition from dispersed outflow to annular outflow. According to the von Karman criterion, we can define a non-dimensional thickness:

$$s^+ = \frac{s}{\mu_l} \sqrt{\tau_0} \quad (3)$$

where  $\tau$  is always the tangential tension at the liquid-center contact point. One can postulate that, for a particular numerical value  $s_0^+$  (for which  $\tau = \tau_0$ ), purely annular outflow is no longer possible. Taking the fact into account that there are no droplets at the center, one can write as a first approximation:

$$\tau_0 = \frac{f'}{2} \frac{G_g^2}{\rho_g} \left[ \frac{D}{D - 2s_0} \right] \quad (4)$$

$$f' = \frac{a}{(G_g D / \mu_l)^n} \quad (5)$$

(4) gives the pressure loss of a gas having density  $\rho_g$  in a solid pipe of diameter  $D$ . The expression for the friction factor  $f'$ , in which  $\mu_l$  was introduced in place of  $\mu_g$ , takes the fact into account that the laminar thickness of the fluid in contact with the walls is made up of liquid, and not of gas.

The yield of the liquid film is given by:

$$\Gamma_l = \pi D \mu_l f(s_0^+) \quad (6)$$

where  $f(s_0 +)$  depends on the velocity profile in the liquid film. We then have:

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$$G_s = \frac{x}{1-x}; G_t = -\frac{x}{1-x} \frac{4g_t}{D} f(s_0 +) \quad (7)$$

From (3), (4), (5), and (7) we can deduce:

$$s_0 = A \cdot D \sqrt{\frac{\tau_t}{\tau_s}} \left[ \frac{1-x}{x} \left( 1 - \frac{2s_0}{D} \right)^2 \right]^{1-n} \quad (8)$$

where all the constants are grouped in A.

In Figure 3

$$\frac{s_0}{D} \sqrt{\frac{\tau_t}{\tau_s}}$$

was given as a function of

$$\frac{1-x}{x} \left( 1 - \frac{2s_0}{D} \right)^2$$

for water at constant temperature and two different diameters. It can be seen that the correlation of  $s_0$  is satisfactory by choosing  $A = 0.114$  and  $n = 0.27$ .

4. In order to be able to draw the curve  $s/s_0$  as a function of  $\tau_i - \tau_0$ , it is necessary to know the value of  $\tau_i$ . The equilibrium of the forces between the two sections 1 and 2 of the pipe, assuming that the static pressure has the same value throughout the entire section, makes it possible for us to write:

$$\tau_i = \frac{D-2s}{4} \left\{ \frac{\Delta p}{\Delta z} + g_{ti} \left[ \left( \frac{D}{D-2s} \right)^2 - 1 \right] - g_{tm} \left( \frac{D}{D-2s} \right)^2 \right\} \quad (9)$$

where  $\Delta p / \Delta z$  is the pressure decrease per unit of pipe length and  $\rho_m$  is the real density of the mixture in the pipe.

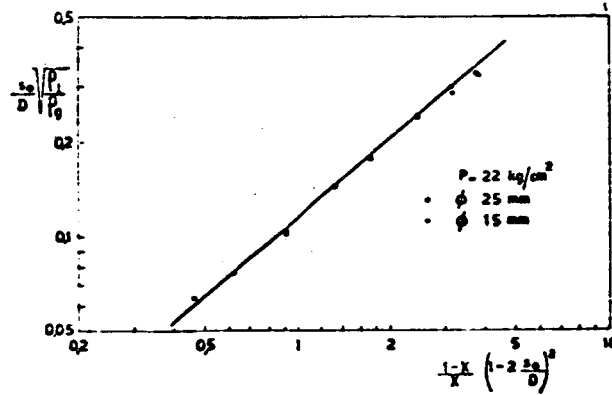


Figure 3

This quantity is difficult to measure, because it is necessary to know the local distribution of the phases, which was only done in our case for a limited number of points. If  $\rho_m$  is not known, by way of an approximation the following expression can be used:

$$\frac{1}{\tau'_m} = \frac{x}{\tau_s} + \frac{1-x}{\tau_l} \quad (10)$$

which leads to a value of  $\tau_i$  ( $\tau'_i$ ) which is a little different ( $\tau'_i > \tau_i$ ). In any case, in Figure 4 the values of  $s/s_0$  (where  $s$  is the measured value and  $s_0$  was calculated with (8)), are given as a function of  $\tau_i$ , when one knows  $\rho_m$ , or of  $\tau'_i$ . Diagrams 4a and 4b show the difference in the two particular cases. It can be seen that the value of  $K$  in (2) is almost as constant in the case of water as it is in the case of alcohol, but for alcohol its value is very different. This can be attributed to the difference between the surface tension of the two liquids.

5. There is every reason to believe that the thickness of the liquid film at the walls plays a very important role in the heat transfer.

In the particular case of the water-vapor system for water, in a great many experiments it was found that the thermal exchange coefficient for a dispersed outflow is, within the dispersion limit of experimental values, a linear function of the heat flux:

$$h = a + b\Phi = a(1 + \beta\Phi) \quad (11)$$

On the other hand, if it is assumed that the film is not the source of the ebullition, the total decrease in temperature between the heating surface and the two phase fluid is the sum of the two terms  $\Delta T_1 + \Delta T_c$ , in which the former is caused by the passage of heat along the liquid layer which is probably superheated, and  $\Delta T_c$  is caused by the evaporation process and the internal surface of the liquid film. One can write:

$$\frac{\Delta T}{\Phi} = \frac{1}{h} = \frac{1}{h_i} + \frac{1}{h_e} = \frac{s}{\lambda} + \frac{1}{h_e} \quad (12)$$

From (11) and (12), we then obtain:

$$h = \frac{\lambda h_e}{\lambda + s h_e} = a(1 + \beta\Phi) \quad (13)$$

For  $\Phi \rightarrow 0$ ,  $s = s_a$  (thickness under adiabatic conditions) and therefore:

$$h(\Phi \rightarrow 0) = h_0 = \frac{\lambda h_e}{\lambda + s_a h_e} = a \quad (14)$$

$$1 + \beta\Phi = \frac{1 + (h_e/\lambda) s_a}{1 + (h_e/\lambda) s} \quad (15)$$

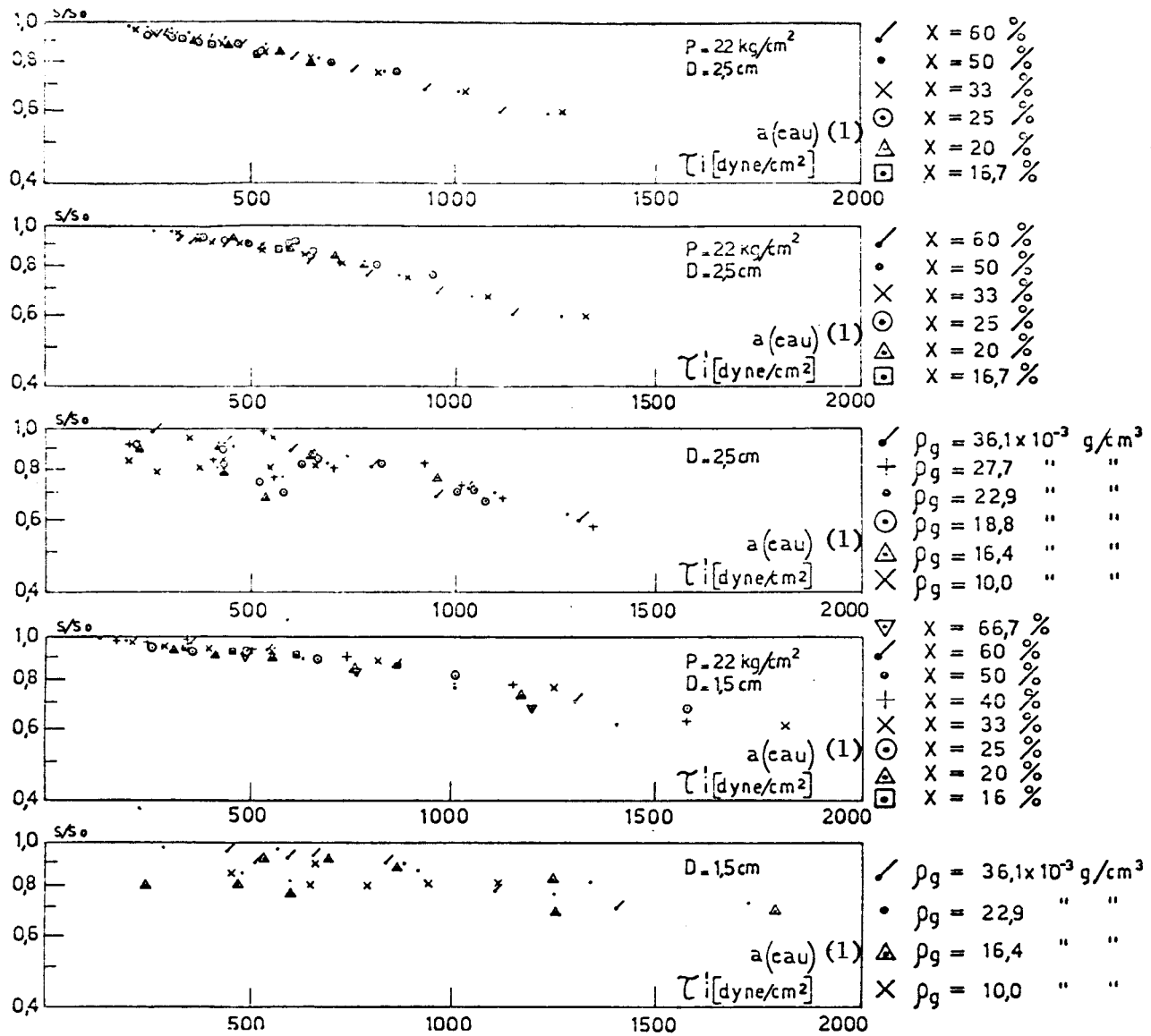


FIG. 4a

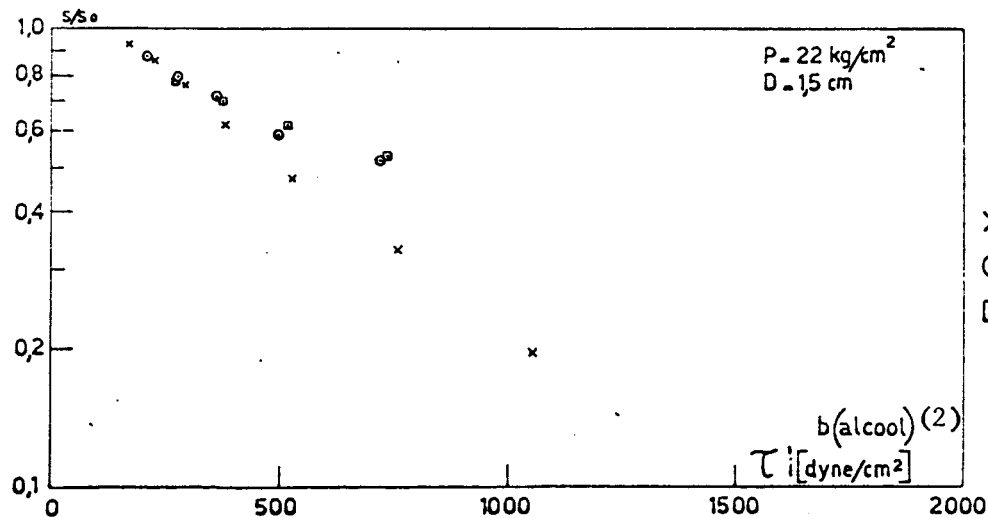


FIG. 4b

(1) - water; (2) - alcohol.

If we make the postulation that the "burnout" condition,  $\Phi = \Phi_c$ , is reached when the liquid film thickness is negligible, (it is not of great importance to establish the fact of whether it is really 0 or whether it is destroyed by mechanical instability under these conditions) we have:

$$s_a = \frac{\lambda \beta}{h_c} \Phi_c \quad (16)$$

At constant pressure and temperature,  $\lambda$  is constant; the experiments showed that  $\beta$  is also constant or varies very little. For  $h_c$  the following expression is obtained, under the slightly restrictive hypotheses of high yield ratio:

$$h_c = (GX)^{0.5} D^{-0.2} \quad (17)$$

We then have:

$$s_a = \frac{B h_c}{(GX)^{0.5}} \quad (18)$$

where all the constants are brought together in B (for constant diameter). In Figure 5, the curve of  $s_a$ , deduced from the measured values of  $\Phi_c$  is drawn using an arbitrary scale for one particular case. As can be readily seen, the behavior of  $s_a$  very closely resembles that deduced from the adiabatic measurement shown in Figure 2.

6. In conclusion, it can be stated that there is no doubt that, in dispersed two-phase outflows, the adiabatic experiments are of

great help in interpreting the heat transfer phenomena. In this article, we wished only to provide an example of the possible connections. This work

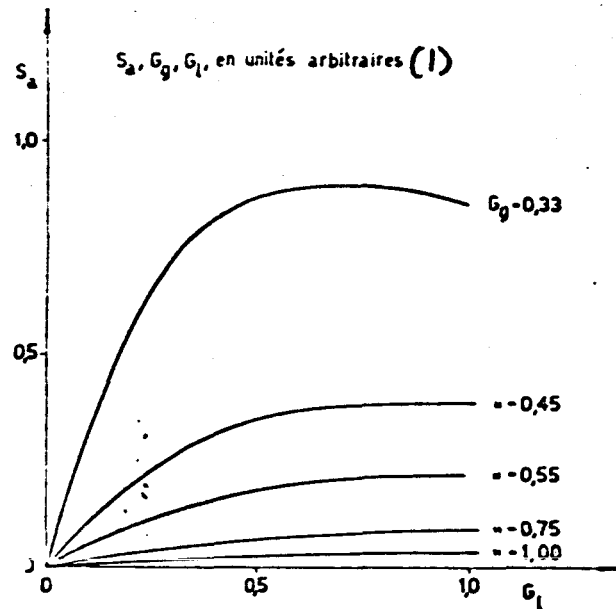


Figure 5

(1) Arbitrary Units

will be continued, and we hope, by means of even more careful experiments, to determine absolutely the role which the liquid film thickness and the surface tension of the liquid play with respect to the heat exchange coefficient and to the critical flux ("burn-out").

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